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Utilization of palm solid residue as a source of renewable and sustainable energy in Malaysia

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ABSTRACT

Today, global energy consumers are addicted to fossil fuels such as natural gas, oil and coal. Although it has been anticipated that fossil fuels will be depleted soon, these fuels are still dominant as the primary source of energy in the world. Recently, many efforts have been done to substitute renewable alternative fuels to reduce dependency on fossil fuels. Biomass as one of the earliest energy sources appears to be the most promising renewable energy source due to its numerous resources and its environmentally sound characteristics. Since Malaysia is agriculture based tropical country, many crops such as palm, paddy rice and sugarcane are cultivated in this region. Malaysian palm oil industry generate huge amounts of palm solid residue (PSR) biomass such as empty fruit bunches (EFB), palm fiber, shell, trunks and fronds as byproducts which are capable to be taken into account in the energy mix of the country. In this paper, an overview of the PSR generation from Malaysian palm oil industries and its social and economic effects has been given. Indeed, performance of the direct combustion of PSR in terms of PSR composition, properties, heating value, emissions and its effects on the equipment or the components of the boilers have been reviewed. It has been found that the very high moisture content of PSR of palm industry makes their collection and transportation expensive, therefore energy conversion process could be inefficient and utilization of these materials inside the palm oil mills seems more beneficial.

Contents

Abbreviations: CRR, crop-to-residual-ratio; EARS, early agglomeration recognition system; EFB, empty fruit bunches; FFB, fresh fruit bunches; FELDA, Federal Land Development Agency; FELCRA, Federal Land Consolidation Rehabilitation Agency; GW, global warming; GHGs, greenhouse gases; MPOB, Malaysian Palm Oil Board; NO_x, oxides of nitrogen; PAH, polycyclic aromatic hydrocarbons; PM, particulate matter; PSR, palm solid residue; RSE, renewable and sustainable energy; RISDA, Rubber Industry Smallholders Development Authority; SAF, surplus-availability-factor; SO_x, oxides of sulfur; VOC, volatile organic compounds

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1. Introduction

Today, around 80% of total world energy consumption has been supplied by fossil fuels such as coal, natural gas and oil. However, it has been anticipated that these non-renewable fuels will be exhausted within 50 years. Indeed, global warming (GW) has emerged as a major problem due to increasing rate of greenhouse gases (GHGs) generated from fossil fuel combustion [1–4]. It is expected that the temperature of the world will increase around 5.8 °C by the year 2100 compared to the year 1990 [5]. Carbon dioxide (CO_2) as the main GHGs generated by an upward trend during the last decade and total CO_2 emission from consumption of energy was reported to be 32,578.645 million tons in 2011. Therefore, development of renewable and sustainable energy (RSE) resources play a crucial role in the future of human life due to their renewability and environmentally friendly characteristics. Biomass as one of the earliest source of energy is a kind of RSE with very especial properties [6–15]. Currently, around 10–15% of world energy demand has been supplied by biomass which in developed countries supplies more than 10% of the total energy demand and in developing countries biomass contribution to total energy consumption has been estimated around 3% [16]. Any organic matter derived from animal materials or plants such as animal and human waste, organic industrial, forest wood, agricultural left overs, crops, forestry processes and seaweed are known as biomass. Solid, liquid and gaseous biomass fuels have been applied in energy generation industry using a variety of feedstock such as cattle and coal biomass [17], solid sludge and solid waste [18], cellulosic ethanol [19] and food and garden wastes [20]. Solar energy derived from plants converted into chemical energy by photosynthesis process and stored in the form of vegetation biomass. Palm solid residue (PSR) biomass is the organic matter derived from palm trees in tropical countries like Malaysia, Indonesia and Thailand as a result of photosynthesis. Photosynthesis is the process by which solar energy is converted into chemical energy by plants with the help of a pigment known as chlorophyll as given in Eq. (1).

$$6CO_2 + 6H_2O + \text{sunlight} + \text{chlorophyll} \rightarrow C_6H_{12}O_6 + 6O_2 + \text{chlorophyll} \quad (1)$$

This process applies carbon dioxide and water in the presence of sunlight to produce glucose. PSR is a renewable fuel with reasonable price which can be stored for use. Moreover, minimum capital is required for energy extraction from this fuel [21,22]. Generally, PSR can be developed with present manpower and material sources in Malaysia, therefore electrical energy can be generated on a large scale at very low cost. Indeed, low gestation period of biomass has improved rural life in Malaysia and has generated many jobs. From an environmental aspect, during burning of PSR, the oxygen from the atmosphere combines with the carbon in the plants to produce CO_2 and water. This CO_2 and water are again available for palm tree growth and hence the cyclic process continues making PSR a renewable source of energy which does not contribute to global warming. Furthermore, low levels of sulfur and ash in PSR combustion products prevent acid rain formation. In general, air pollution can cause health problems and it can also damage the environment and property. It has been reported that coal is responsible for 30–40% of worldwide CO_2 emission [23]. Unlike fossil fuel PSR does not lead to substantial GHGs production and GW phenomena [24]. The environmental benefits include reduction in air and water pollution and reduced SO_2 and CO_2 emission have highlighted the environmentally sound characteristics of PSR utilization in Malaysia [25–27]. Although it has been claimed that dioxins as toxic and bio-accumulative chemicals can be emitted from biomass combustion, the dioxin emissions found in PSR boilers are controllable and can be reduced in an effective manner [28]. It is necessary to avoid high temperature biomass combustion due to negative effects such as volatilization of mercury, leaving solid ash and slag residuals which emerge in biomass combustion when the temperature of the process increases up to 575 °C [29].

1.1. Palm tree plantations in Malaysia

Oil palm plantations in Malaysia have been discussed in detail by Corley and Tinker et al. [30]. Generally, palm trees are planted in Malaysia for food applications like frying oil and cooking oil. However, palm oil industries generate huge amounts of biomass residue which can be utilized in different industries [31–34]. Fig. 1 illustrates the summary of biomass byproduct generation in palm oil industries in Malaysia. Indeed, Fig. 2 demonstrates the types of different byproducts generated annually from palm oil industry as palm biomass in Malaysia [35].

In recent decades, Malaysian government has introduced biomass as the fifth fuel resource after petroleum, gas, coal, and hydro. Wood chips, agricultural waste, effluent sludge and domestic wastes have been mentioned as the most important biomass resources in Malaysia [36,37]. Moreover, due to specific weather circumstances, palm biomass has been developed in huge quantities in Malaysia [38]. In the harvesting process of palm crops and also in the palm oil mills, some solid residues and leftovers like EFB, palm fiber and palm shell from palm oil fruit remain. PSR can be applied as a substitute alternative fuel for energy generation in industrial boilers and consequently, can help solve the problem of very high fossil fuel prices as well as environmental issues and global warming. The amount of PSR from agricultural products can be projected by their productivities, surplus-availability-factor (SAF) and crop-to-residual-ratio (CRR). SAF is the rate of unused PSR or residue left-overs which are not applied regularly and the CRR is the amount of PSR generated per one unit mass of the produced palm. The extracted energy from solid by-products of palm industry is calculated from the quantity of PSR and the lower heating value of PSR [39]. Elaeis guineensis from western Africa and Elaeis oleifera from tropical Central America and South America are mentioned as the two origins of oil palm and of the two, Elaeis guineensis has been cultivated on a wide scale in South East Asia [40]. Today, the palm trees plantation in Malaysia are continuously increasing due to Malaysian government strategies for palm oil-based biodiesel production [41]. Malaysian Palm Oil Board (MPOB) reported that the land area committed to oil palm plantation in 2012 accounted for around 5076929 ha. Federal Land Development Agency (FELDA), Rubber Industry Smallholders Development Authority (RISDA), Federal Land Consolidation Rehabilitation Agency (FELCRA), private estates, state agencies and independent smallholders are the main palm trees ownership forms in Malaysia.Table 1 depicts oil palm planted areas in different states of Malaysia at the end of 2012 and Table 2

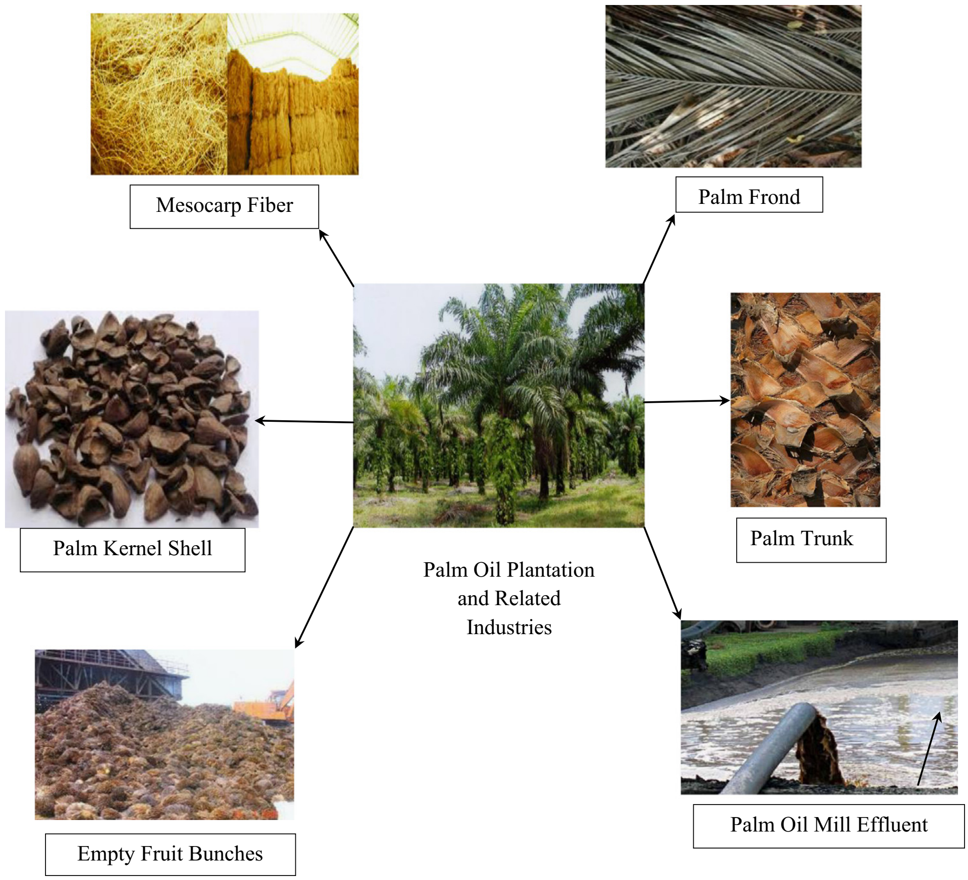

Fig. 1. Biomass byproducts generation in Malaysian palm oil industry.

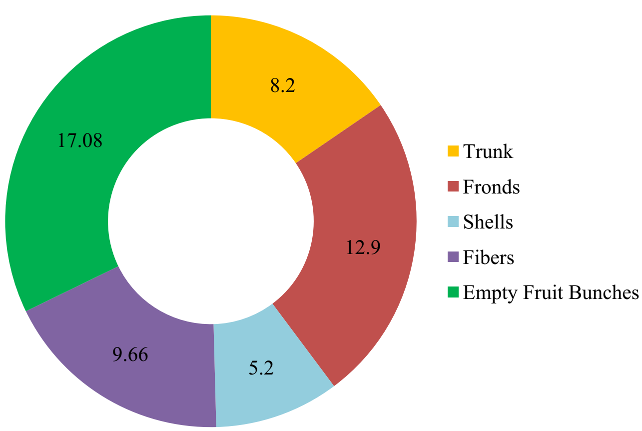

Fig. 2. Palm biomass production in Malaysia (million tons per year) [35].

Table 1
Oil palm planted area in different states of Malaysia [42].

State	Mature	%	Immature	%	Total	%
Johor	618,353	86.59	95,777	13.41	714,130	14.07
Kedah	76,181	90.13	8,342	9.87	84,523	1.66
Kelantan	91,182	66.23	46,497	33.77	137,679	2.71
Malacca	48,718	92.75	3,806	7.25	52,524	1.03
Negeri Sembilan	143,580	85.94	23,496	14.06	167,076	3.29
Pahang	595,799	85.09	104,402	14.91	700,201	13.79
Perak	338,100	88.99	41,846	11.01	379,946	7.48
Perlis	197	69.37	87	30.63	284	0.01
Penang	13,264	97.85	292	2.15	13,556	0.27
Selangor	124,080	90.77	12,611	9.23	136,691	2.69
Terengganu	136,509	79.60	34,984	20.40	171,493	3.39
Sabah	1292,757	89.61	149,831	10.39	1442,588	28.41
Sarawak	874,152	81.22	202,086	18.78	1076,238	21.20
Total	4352,872	85.45	724,057	14.55	5076,929	100

demonstrates the ownership of oil palm planted area in Malaysia [42].

Palm trees usually have a vertical trunk and feathery leaves and every year around 20–40 new leaves known as palm frond are grown. Bunches of palm fruit develop between trunk and base of the new fronds. Generally, 5–6 years after plantation the first crop of fresh fruits can be harvested and each tree can provide palm fruit for 25–30 years [43]. The weight of fresh fruit is around 10 to 40 kg. Each fruit has a spherical shape and a black color before turning to orange–red when ripe [44]. Fig. 3 illustrates oil palm tree and FFB [45]. Indeed, the rate of FFB produced per hectare in different states of Malaysia in 2010 has been demonstrated in Fig. 4 [42].

Table 2
The ownership of oil palm planted area in Malaysia [42].

Category	Hectares	(%)
RISDA	78,634	1.5
FELCRA	167,361	3.3
State Agencies	306,187	6.0
Independent smallholders	691,688	13.6
FELDA	706,069	13.9
Private states	3126,990	61.6
Total	5076,929	100.0

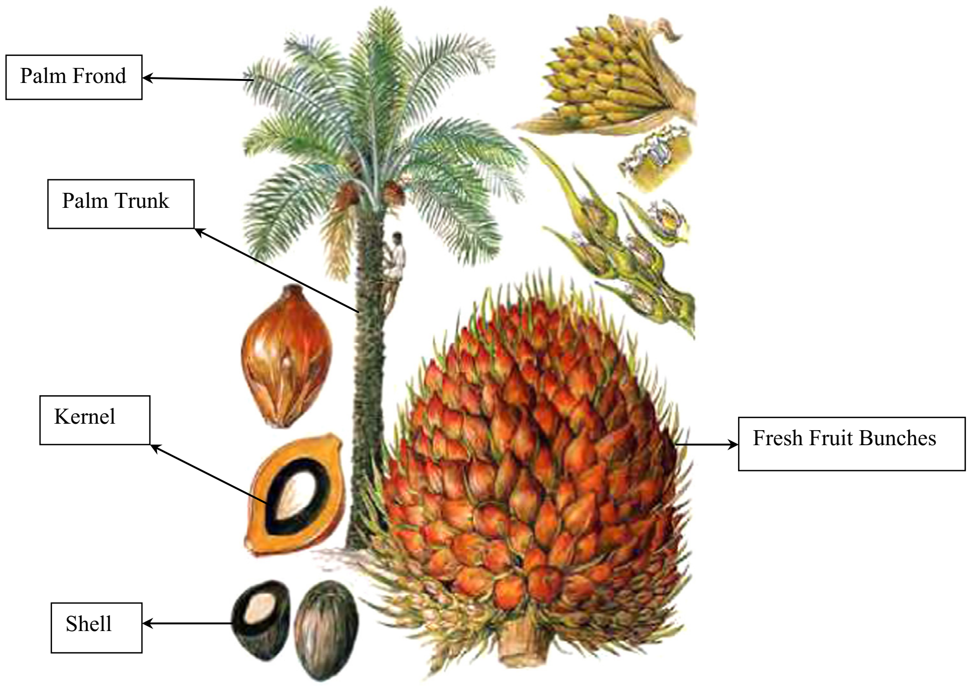

Fig. 3. A typical palm tree and FFB [45].

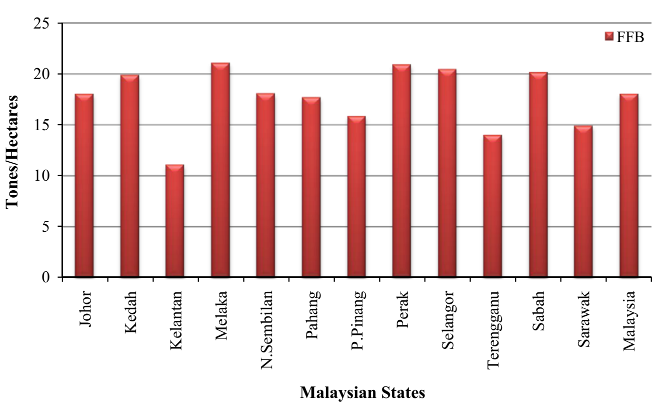

Fig. 4. The rate of produced FFB (tones/hectares) in different states of Malaysia in 2010 [42].

1.2. Palm solid residue generation in Malaysia

Palm oil EFB is a solid waste residue generated from palm oil mills. Harvested fresh fruit bunches (FFB) are sterilized in a horizontal steam sterilizer in order to loosen the fruits from bunches and to deactivate pericarp enzymes. Then a rotary drum thresher is used to remove the sterilized fruit from bunches. EFB are conveyed to the warehouse and the sterilized fruits are applied as feedstock for oil production in palm oil extraction process. In palm oil production chain some cyclones are employed to separate fibers and nuts from the effluent generated by screw type press, consequently kernels and shells are produced from nuts. The former is applied in kernel oil mills and the latter is solid waste [46]. It has been stipulated that 100 t of FFB can generate 5 t of shell, 20–22 t EFB and around 14 t oil-rich fiber as shown in Fig. 5 [43].

In order to utilize a fuel such as PSR in the boilers, chemical characteristics of the fuel should be identified to determine the potential energy generation of the fuel and environmental problems generated from fuel combustion emissions. Therefore, structural analysis, ultimate analysis and proximate analysis should be implemented. In the molecular structure of PSR various amounts of lignin, cellulose, hemicellulose as the main three constituents called 'lignocellulose' and small amounts of lipids, starches, proteins and simple sugars exist. Biomass also consists of inorganic constituents and a fraction of water. The largest components of lignocellulose are cellulose, hemicellulose and lignin respectively. Typically, the main components of dry PSR are oxygen with around 30 to 40 wt%, carbon with 30 to 60 wt% and hydrogen at around 5–6%. The percentage of N, S, C, O and H can be assessed by PSR ultimate analysis to estimate the heating value of PSR and to identify the impact of this material on the environment. Indeed, proximate analysis which is important in PSR combustion analysis assesses the percentage of ash content, volatile matter and fixed carbon [47]. Table 3 depicts proximate and ultimate analysis of EFB generated from Malaysian palm oil mills based on experimental results published by Hamzah et al. [48].

In PSR combustion, in the presence of excess amounts of air the total energy released in the form of heat is known as PSR heating value or calorific value. Gupta et al. [49] measured the heating value of biomass theoretically based on Eq. (2).

$$\text{HV (kJ/kg)} = 33{,}823*C + 144{,}250*(H - O/8) + 9419*S \tag{2}$$

where C, H, O, N and S are the mass fractions of these elements in the biomass.

It is noteworthy that the given lower heating value of PSR in Table 3 shows some discrepancy with theoretical results because Eq. (2) is valid when the biomass oxygen content is less than 10%. Compared to fossil fuel the heating value of PSR is very low which creates problems such as flame stability. Therefore blending PSR with fossil fuels like coal or co-firing method can reduce the flame stability problems [50].

1.3. Social and economic impacts of PSR utilization in Malaysia

Although biomass and coal co-firing technologies have received special attention, environmental and economic feasibility study is required for development of these projects [51,52]. There are some

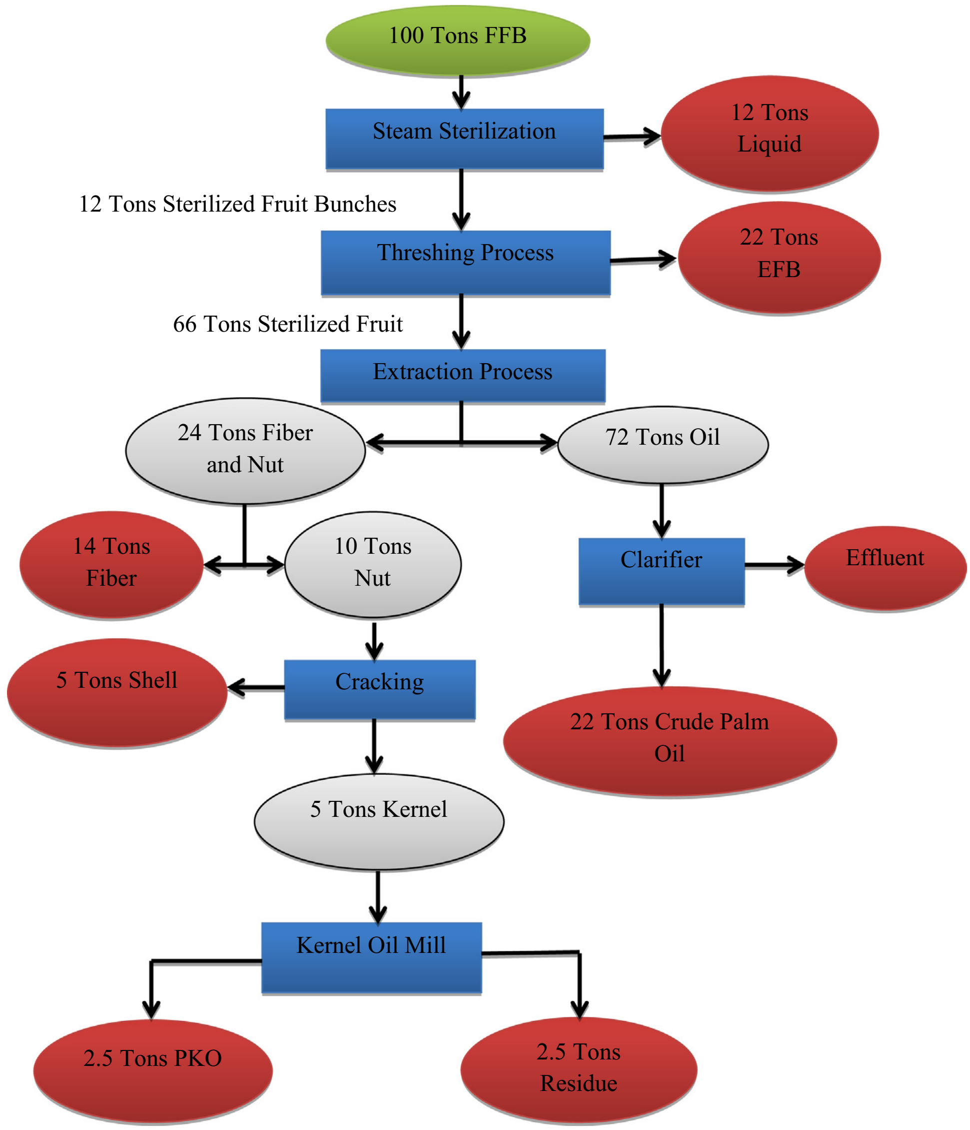

Fig. 5. The process of EFB generation as solid waste from Palm oil mills [43].

Table 3
Analysis of EFB generated from Malaysian palm oil mills [48].

Proximate analysis		EFB from Malaysian palm oil mills
Moisture	**wt%**	**8.75**
Volatile matter	wt%	79.65
Fix carbon	**wt%**	**8.60**
Ash	wt%	3.00
Ultimate analysis		
C	wt%	48.79
H	**wt%**	**7.33**
O	wt%	40.18
N	wt%	0
S	wt%	0.68
Others	wt%	0.02
Ash	wt%	3.00
Lower heating value	MJ/kg	18.96

crucial factors which identify whether biomass feedstock is suitable for energy use. Some non-governmental organizations (NGOs) have debated expanding the agricultural sector for energy generation or for food because so many people in the world are facing famine. However, many biomass researches are focusing on inedible biomass hence no competition with food purposes [53].

On the other hand, the cost of energy generation from PSR depends on high yield of dry material per unit of land (dry tons/hectare). A high yield decreases the land required for palm plantation and lowers the cost of energy generation from PSR. Generally, the cost of energy generation from fossil fuels is more than biomass fuels [54,55]. PSR not only has conspicuous potential as a fuel source, it also has a more reasonable cost when compared to other renewable energy sources. PSR utilization offers many economic advantages such as utilization of palm forest and palm oil mill residue, harmful emission reduction, fossil fuel conservation, mitigation of the dependence on fuel imports, cultivation of non-farming area [56,57]. Indeed, development of palm oil industry can ensure social sustainability in Malaysia by providing employment opportunities especially in rural areas. The cultivation of energy crops requires a large amount of labor, thus it could deliver valuable benefits to rural communities of Malaysia [58,59]. Abdelaziz et al. [60] stipulated that the annual bill saving in industrial boilers when biomass and fossil fuel are applied simultaneously is around US$270,000 based on 80% diesel and 20% biomass consumption, US$500,000 in the case of 60% diesel and 40% biomass consumption and US630,000 in the case of 50% diesel and 50% biomass consumption. Storage, logistics and transportation costs are a part of the total overall cost of a PSR-fired

boiler. It has been stated that 20–50% of biomass delivered cost is due to transportation and handling activities. Palm trees and consequently palm oil mills are geographically dispersed all over Malaysia and may lead to higher transportation cost. The supply of PSR and their storage are also a major concern in providing for continuous boiler operation. If PSR is transported straight away from palm oil mills or cultivation area, it may result in less cost effectiveness [23]. Fig. 6 depicts the supply chain of PSR in Malaysia [61].

PSR storage is a critical link in the respective supply chain. Biomass storage has been proposed in some investigations [62–64]. While on-field methods may be low cost, PSR on-field storage may lead to PSR material loss and the moisture of PSR cannot be controlled and reduced to a desired level, possibly leading to critical problems [61]. Moreover, some health and safety problems can be generated due to the formation of spores and fungus [65]. Intermediate storage between the palm oil plantation area or palm oil mills and the power plants has been suggested to solve the aforementioned problems. However, by storing the PSR in intermediate storage delivered cost can increase 10–20% [44]. Thus, setting up PSR storage facilities near biomass power plants can be the best solution to deal with these problems. Drying process of PSR can be accelerated by tapping waste heat from the power plant to prevent fungus and spore formation and may also prevent material decomposition. Meanwhile, transportation costs are also decreased compared to the use of intermediate storage method. Rentizelas et al. [66] stipulated that a combination of multi-biomass approach with relatively expensive storage methods is more advantageous. Indeed, low cost biomass storage ensures safety and health and reduces technological risks.

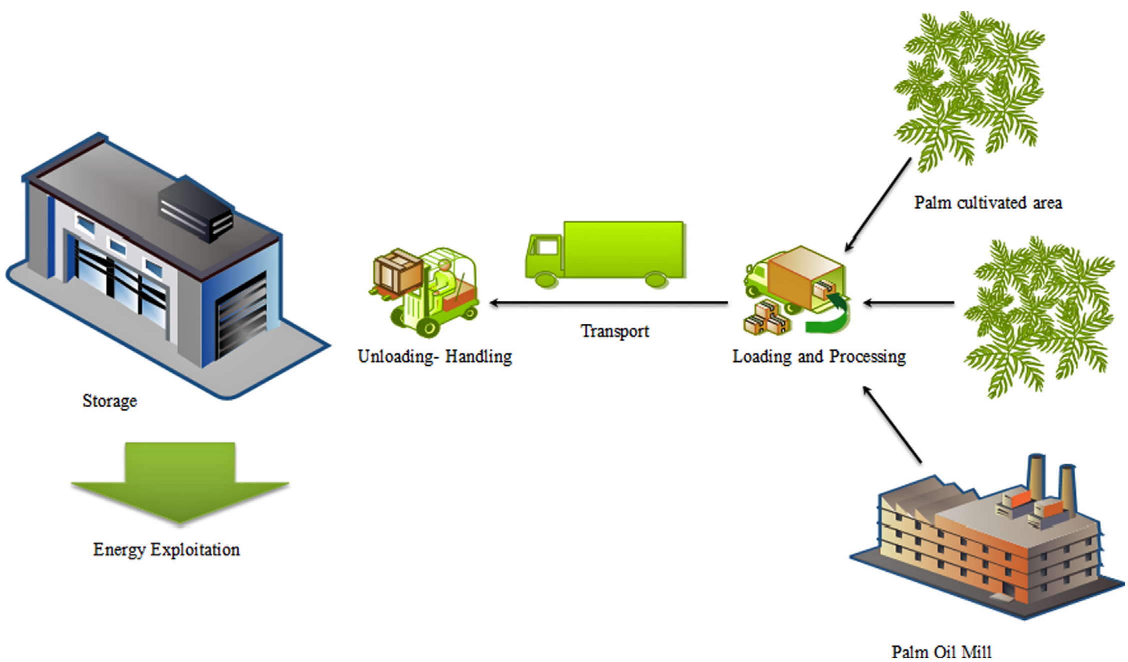

Fig. 6. Common supply chain of PSR [61].

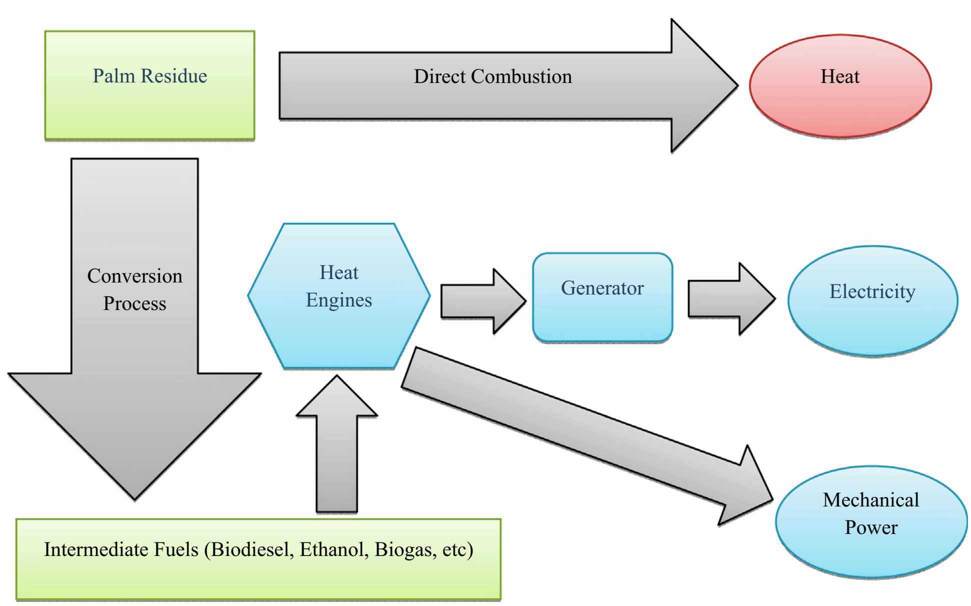

Fig. 7. Different Methods for converting the energy of palm residue into convenient energy [71].

2. PSR energy conversion

Biomass energy conversion technologies for industrial utilization purposes are growing at a very fast pace due to the increasing rise in oil prices and the environmental issues generated by fossil fuel utilization. Most developing countries find it hard to keep up with biomass production because the level of technology is beyond their manpower as well as their manufacturing and technological capability. Added to this is the unavailability of local materials and parts for the fabrication of these conversion units. Biological processes, mechanical methods, thermal and chemical processes are the most important methods for PSR energy extraction. In mechanical processes, dried EFB is fed into briquetting equipment to produce briquettes. Briquette EFB have very good characteristics for fuel applications in conventional combustion in co-firing plants compared to the initial form of EFB [67–69]. The low moisture of pelleted EFB, very high mechanical strength and size uniformity are the main advantages of the pelletizing process which has a great effect on the quality of EFB combustion process. It has been proven that the blending of briquette EFB with waste paper can improve its combustion properties [70]. Fig. 7 shows the different methods for converting the energy of palm residue into convenient energy [71].

Although PSR must be converted into chemical, electrical or mechanical energy to have widespread use, its conversion into heat energy is still the most efficient process. These take the form of solid fuel like charcoal, liquid fuel such as ethanol or gaseous fuel like methane [71]. This fuel can be used in a wide range of energy conversion devices to satisfy diverse energy needs. In general, conversion technologies for PSR utilization may either be based on bio-chemical or thermo-chemical conversion processes. Fig. 8 demonstrates the pathway of PSR energetic utilization [72,73].

2.1. PSR direct combustion and co-firing

Direct combustion chambers are divided into two broad categories and are applied for generating either direct heat or steam. Fuel cell furnaces, ovens and spreader-stoker have been applied in two-stages. The first step is for drying and gasification, and the second stage is for complete combustion. Rotating or vibrating grates are employed to facilitate ash removal with some requiring water cooling. Suspension and fluidized bed chambers are applied with fine particle PSR feedstock and liquids. In suspension furnaces the PSR particles are burnt while being kept in suspension

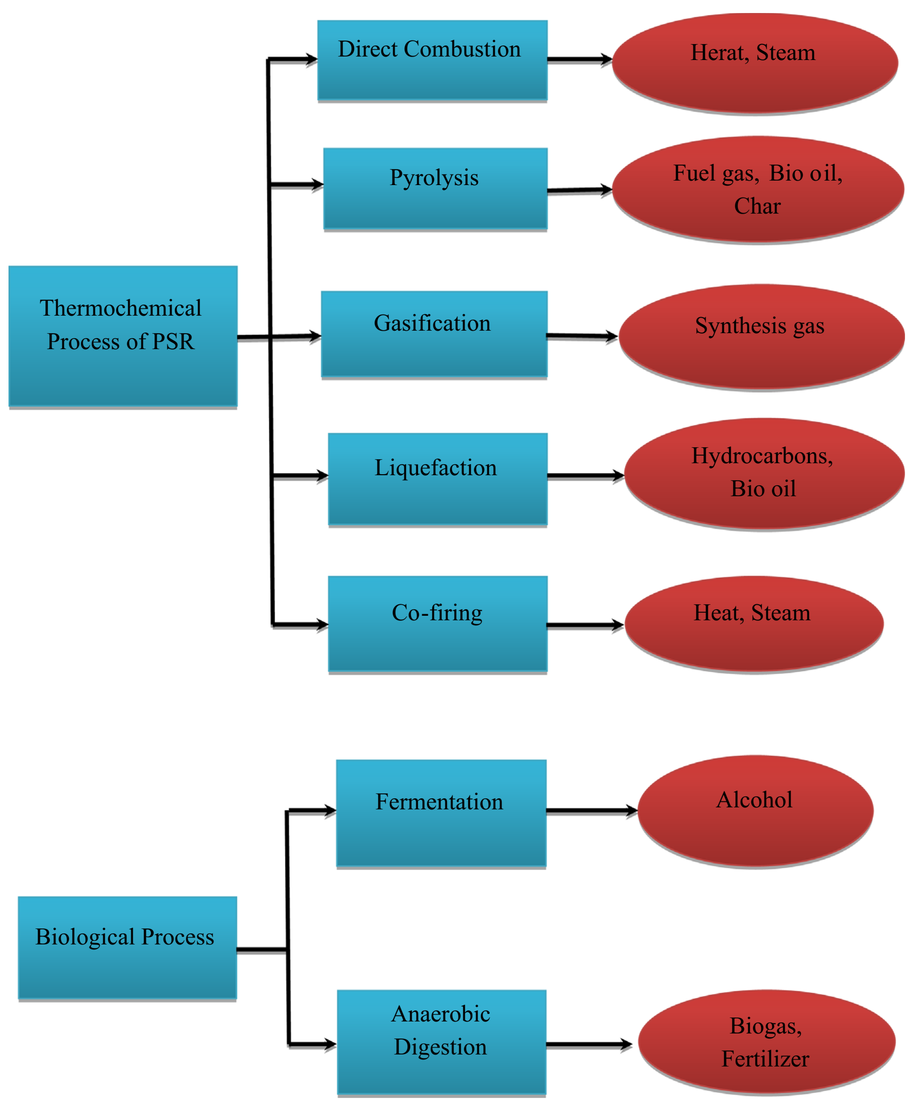

Fig. 8. Pathway of PSR energetic utilization [73].

by the injection of turbulent preheated air which includes PSR particles. In fluidized bed chambers a very hot bed of sand at temperatures 500–900 °C prepares the combustion medium, into which the PSR fuel is either dropped if it is dense enough to sink into hot sand or injected if particulate or fluid. In this system the need for grates is obviated, but it requires some systems for preheating the sand or air, and may require water cooled injection systems for less bulky PSR feedstock and liquids. It has been stipulated that the best system which has allowed PSR feedstock an immediate and cheap entry point into the energy market is the co-firing of fossil-fuel such as coal with PSR feedstock [63]. Traditionally, grate boilers have been applied for solid fuel combustion. These boilers are suitable for many types of fuels such as wood, peat, coal, straw and waste fuels. Grate boilers are suitable for co-firing combustion systems and they have simple structure and operation, therefore initial investment and their maintenance is not very costly. However, grate boiler efficiency is lower than fluidized bed systems and their pollutant formation is greater. In electricity generation, application of co-firing system has many advantages. Where the energy conversion facilities are situated near forestry or a palm oil mills, huge amounts of low cost PSR is available. On the other hand, it has been accepted that fossil-fuel power plants are usually highly polluting in terms of sulfur, CO_2 and other GHGs [64]. Therefore, with some simple modifications, co-firing combustion with PSR represents a cost-effective means for meeting more stringent emissions targets. Co-combustion of coal and biomass in large plants creates a potential for high electric efficiencies due to high steam parameters and technical measures for efficiency improvement. Furthermore, large thermal power plants can lead to an overall saving of fuel in comparison to fossil and biomass plants. The possibility of co-fire biomass in coal-fired boilers offers a huge potential at the European level as well as worldwide. Co-combustion is commonly used in the USA, Finland, Denmark, Germany, Austria, Spain, Sweden and many other IEA countries. The production capacity of a co-combustion plant is typically 50 to 700 MW, and there are also a few units between 5 and 50 MW. The most common method is pulverized fuel combustion. However, the most suitable technology is fluidized bed combustion when the amounts of PSR in the fuel flow are high and the moisture content of PSR is high. Low SO_2 and nitrogen content of PSR and nearly zero net CO_2 emission levels allow PSR to offset the higher sulfur and carbon content of conventional fuel [65]. Indeed, if forestry processing plants or palm oil mills wish to make more efficient use of the PSR produced by co-generating electricity, but have a specific seasonal schedule for the operation of some components, PSR co-firing with a conventional fuel allows for economical electricity generation all year. Palm oil mills can generate large amounts of electricity during the harvesting and processing season; however, during the off-season the plant remains idle, thus electricity generation can be guaranteed year-round by burning alternative fuel in power generation [74]. It has been stated that NO_x formation in co-firing biomass combustion can be mitigated by around 15% compared to direct biomass combustion [75–77]. Indeed, ash composition changes in different blends; therefore desirable ash composition is achieved with the application of only 20% biomass in mixed fuel in co-firing systems [53].

2.2. Gasification of PSR

Gasification is a thermo-chemical method for converting PSR into a low medium energy gas utilizing sub-stoichiometric amounts of oxidant. Air gasification is the simplest form of gasification in which PSR is subjected to partial combustion with a limited supply of air [4]. In direct gasification the feedstock is oxidized by an oxidant and the reactant specious prepare the needed energy and maintain the temperature of the process, however an external energy source should support indirect gasification systems because this process does not occur in the presence of an oxidizer [78]. The presence of nitrogen plays a crucial role in the heating value of generated gas from gasification; therefore released gas from indirect gasification has higher heating value. Fig. 9 shows direct and indirect gasification process schematically [79].

The most important advantages of air gasification are its low cost, simplicity and very high reliability. However, an important drawback is their low colorific value. Therefore, it seems distribution of the produced gas is not commercially viable and it should be applied for on-site purposes. In oxygen gasification, the generated gas is of high energy content due to pure oxygen is utilization in the process. However, oxygen plants are one of the priorities of this method which increases the total cost of oxy-gasification [80]. The process of feedstock conversion into gaseous fuel occurs in a reactor known as a gasifier. Fixed bed gasifier (upward draft and downward draft), fluidized bed (bubbling and circulating) and indirect gasifier (char and gas) are three types of gasifier methods. The updraft gasifier is the simplest air gasifier method. Air is charged at the bottom of the biomass bed next to the hearth zone. The temperature of generated gas is usually low. Before biomass reaches the reduction zone, it is preheated by the heat of the gas. Materials from the drying zones and distillation

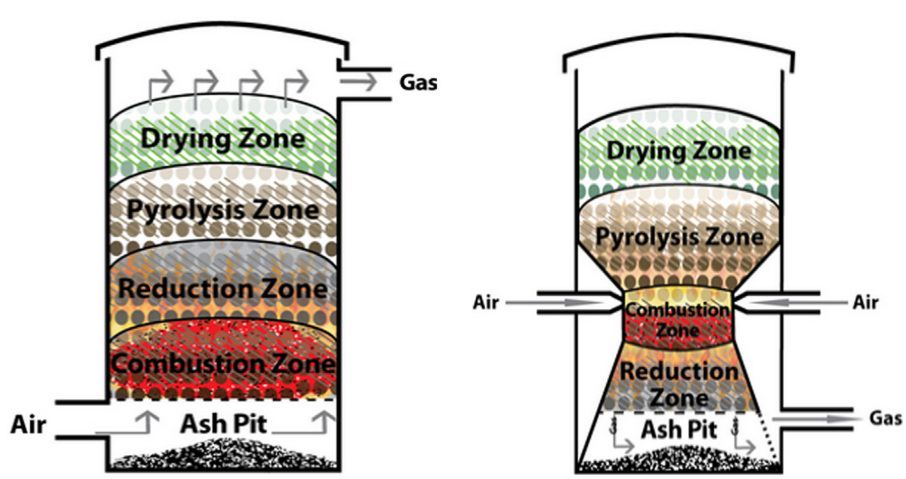

Fig. 9. The schematic of direct and indirect gasification process [79].

area are not passed through the hot bed because they usually consist of oil vapor, water vapor and tar. The generated tar vapors in updraft gasifier have negative effects on internal combustion engine operation therefore the downdraft gasifiers are more desirable. In this case air is injected into a downward flowing bed of solid fuel and the outlet of the gas is located at the bottom of the system. Fig. 10 shows the schematic of downdraft and updraft gasifier mechanisms [81,82].

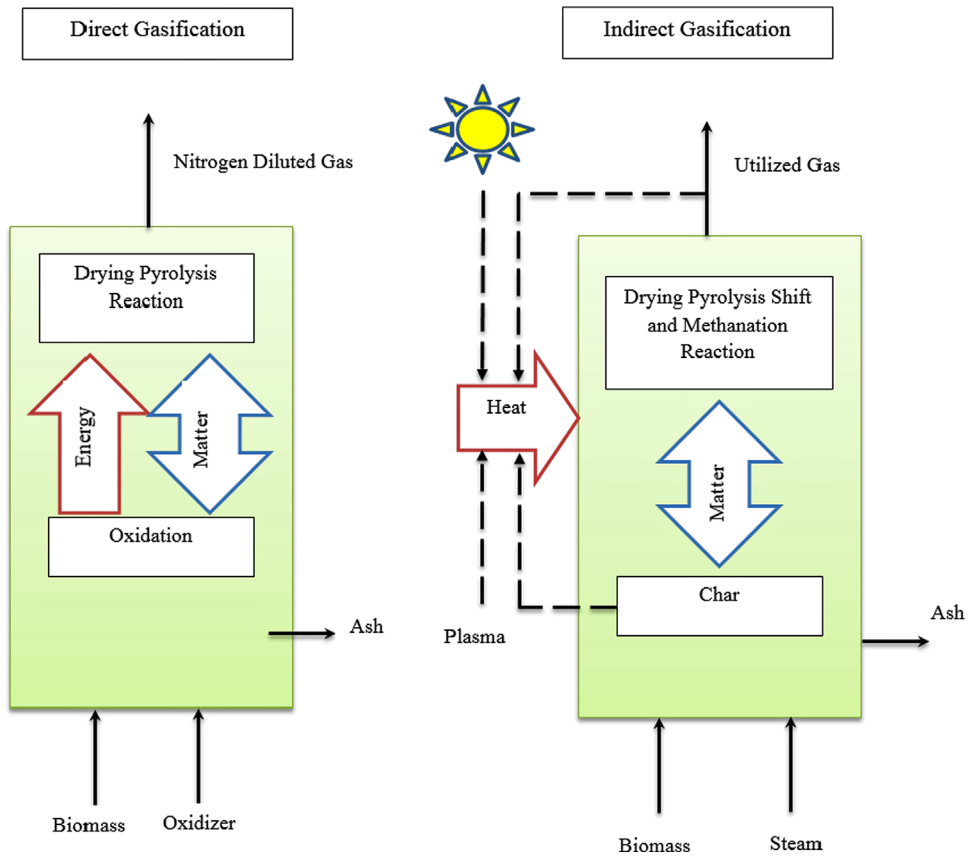

Fig. 10. The schematic of downdraft and updraft gasifier mechanisms [82].

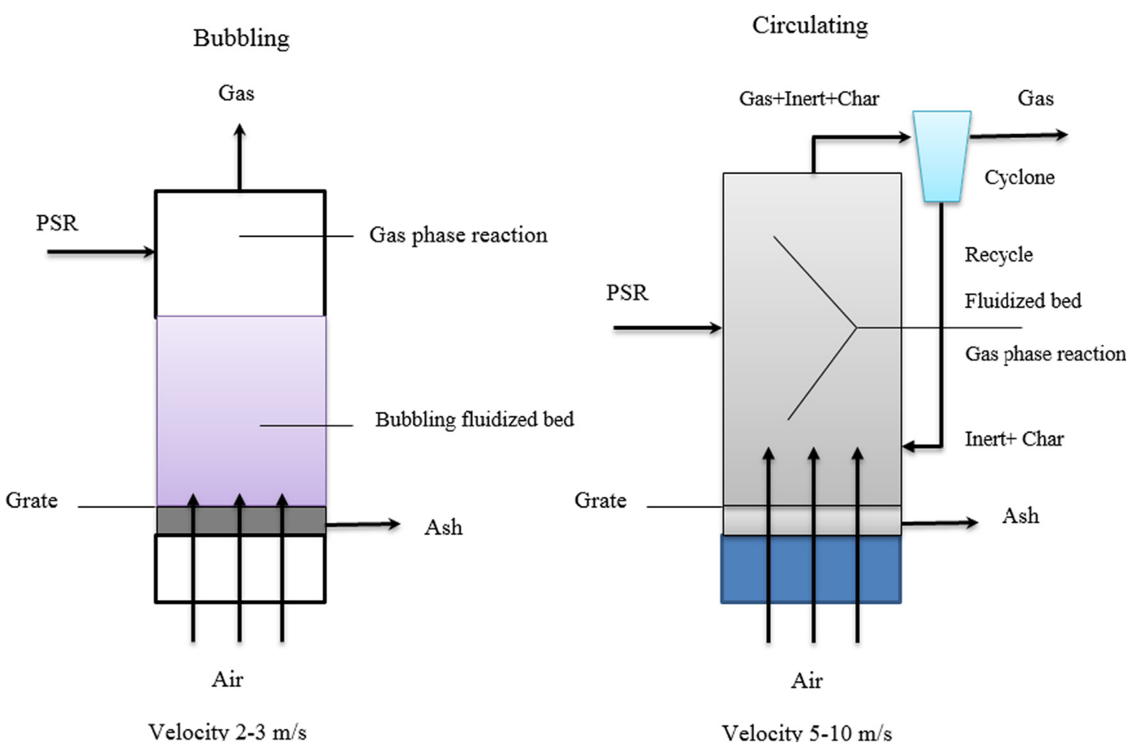

Fig. 11. Schematic diagram of a fluidized bed gasifier [79].

Since high rates of ash could be charged to the system with feedstock during operation of fixed bed gasification system and in order to increase the efficiency of the system, fluidized bed gasification was developed. PSR is fed to the fluidized bed gasifier through a fluidized bed of inert particles. Compared to the other types of gasifiers much higher amounts of PSR can be gasified by fluidized bed gasification. In bubbling fluidized bed (BFB) reactor the upward flowing gasification velocity is around 1–3 m/s and the inert bed expansion regards only the lower part of the gasifier. Char and bed sand cannot come out of the system due to their low velocity [83]. In circulating fluidized bed (CFB) upward flowing gasification velocity is around 5–10 m/s. Fig. 11 illustrates the schematic diagram of a fluidized bed gasifier [79].

2.3. PSR pyrolysis

Pyrolysis as a thermal decomposition is an irreversible slow chemical reaction caused by the heat action on PSR in the absence of oxygen to convert PSR into valuable industrial energy feedstock. This low temperatures destructive distillation of PSR leads to solid, liquid and gas products. Some parameters such as heating rate, catalyst, temperature and particle size effect the ultimate products of biomass pyrolysis. Ash and carbon are the main components of solid residue in PSR pyrolysis and methanol, acetone, water, tar and acetic acid generally exit from PSR pyrolysis systems as liquid. Indeed, Hydrogen, CO_2, CO and CH_4 are the most important gases generated in pyrolysis of PSR and some other hydrocarbons such as C_2H_4 and C_2H_6 are emitted on a small scale. Some operations such as primary shredding, drying the shredded material, organic removal, supplementary shredding to fine size, condensation of liquids by cooling of the products and storage of the products is done in typical pyrolysis process. Vertical shaft reactors and horizontal beds are two types of reactors applied in pyrolysis systems. The simplest and cheapest pyrolysis system is the vertical shaft reactors. The amounts of gases released from fast pyrolysis are usually more than solids residue [84].

2.4. Fermentation

In fermentation process, ethyl alcohol can be produced from sugar containing feedstock like PSR in the presence of yeast. Before yeast fermentation, the starch of PSR should be converted into fermentable sugars. Also, some kinds of enzymes can be applied to decompose the cellulose in PSR fibers to produce more ethanol in fermentation process. Catalytic action is needed to break down the large organic molecules of PSR. CO_2 and some spent residues including yeast cells, non-fermentable part of PSR substrate and non-fermented sugars are usually generated as fermentation byproducts [85,86].

3. PSR utilization problems

3.1. Emissions from PSR combustion

In PSR combustion primary pollutant such as particulate matter (PM), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), HC and CO are emitted. Indeed, acid gases like HCl can be formed. In incomplete PSR combustion CO and HC including volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH) are generated [87]. The size of PM including condensed fumes (tars/roils), soot and ash are less than 1 μm which are hazardous for people's health as they are retained in the lung. Generally, a small fraction of NO_x formation in PSR combustion is thermal NO_x because PSR combustors work at low temperatures. NO_x formation in PSR combustion is very sensitive to equivalence ratio. Lean fuel conditions produce high rate of NO_x and fuel rich conditions produce low yields. In fuel rich circumstances the relatively fast conversion of fuel carbon to CO competes for oxygen and leads the combustion phenomena to a reduced availability of oxygen for NO_x formation. On the other hand, bad ozone which irritates lung and eyes and which can create major problems in urban environments can be formed by photochemical combination of NO_x and HC [88,89]. Ozone is also harmful to plants. SO_x are respiratory irritants and their effects are enhanced in the presence of PM due to transport deep within the lung. Both NO_x and SO_x participate in reactions leading to acid rain [90].

3.2. Fouling, deposits, slagging and corrosion issues

In industrial boilers fueled by PSR, some residues such as deposits and fouling in the shape of ash are commonly found on the surface of heat transfer equipment. The slagging is the constitution of molten or partially fused deposits on the chamber walls formed when soften ash is not completely cooled down to solid form. Corrosion is the chemical process where the equipment deteriorates due to reaction with its environment. These problems play a crucial role in designing, cost, lifetime and operation of the system, total emission, efficiency of the boiler, erosion and heat transfer of the boiler [91]. Although PSR is a neutral carbon fuel resource, it may consist of a larger variety of inorganic components compared to coal, thus issues of fouling and corrosion can be a big concern. Sodium and potassium contained in PSR may decrease the melting point of ash, therefore more ash deposition and fouling of the boiling tube occur [16]. Molten phase corrosion, solid phase corrosion and corrosion associated with gas particles are named as the main corrosion mechanism in PSR boilers. It has been stated that the removal process of these problems can be done by leaching the PSR fuel with water. Leaching process decreases the inorganic particles volatilization at temperatures higher than 575 °C. Bakker et al. [92] showed that leached biomass fuel decreases alkali index which then lead to less boiler fouling problems. In order to reduce the deposit, certain additives can be added to PSR fuel. Some additives such as limestone bauxite, magnesium oxide and kaolinite generate high melting point alkali compounds relative to alkali chlorides. The melting point of ash increases by adding these additives, therefore the deposit formation can be decreased.

3.3. Agglomeration

Agglomeration is the process where the material has gathered to form a bulky mass. Defluizization is the main effect of agglomeration in boilers [92]. After a few hours of boiler operation, the ash layer of potassium starts to develop and the agglomerates are formed. Agglomeration in PSR boilers can occur as a result of the accumulation of low-temperature-melting phosphorous and potassium salts or in the presence of silica from calcium and sand from PSR fuel. In this case the silica will react with potassium phosphate to form low-temperature-melting silicates of potassium and calcium, and this phosphorous is bound with calcium. Constitution of agglomeration in PSR should be under control because it is capable of an unscheduled shut down of the boiler system. Nijenhuis et al. [93] stipulated that the implementation of early agglomeration recognition system (EARS) can predict the agglomeration 30–60 min in advance. By implementing a certain monitoring and control system the unscheduled shut down of the boiler can be prevented. Furthermore, by utilization of boiler with co-combustion system the agglomeration formation can be eliminated. Also, by adding certain additives such as dolomite limestone, alumina, kaolin and lime which can coat sand particles by preventing the reactions of potassium

phosphate and silica, the constitution of agglomeration can be decreased. Moreover, alternative bed materials known as Agglostop such as alumina, dolomite, ferric oxide, feldspar and aluminum rich mineral in the boiler bed can decrease the agglomeration problem.

3.4. Financial and political barrier

There are some financial barriers in PSR utilization in power generation such as high energy production cost, lack of support from the government for electricity generation from renewable and sustainable energy sources, lack of appropriate subsidies and tariffs for biomass-fired electricity. In general, the capital cost of PSR power plant is high and there are insufficient incentives available in implementing the system. Indeed, the present fossil fuel power plants are not easily changeable to PSR fuels because new burners are needed which require additional capital. Due to insufficient support from the government in providing incentives, the penetration of PSR into the market is low and insignificant. In addition, technical equipment maintenance has become a big concern of biomass power plants in Malaysia due to the lack of local equipment manufacturers or agents for the efficient conversion of various types of biomass to energy [91].

4. Conclusion

Energy crisis and environmental issues have encouraged the governments of tropical countries like Malaysia to invest in renewable biomass resources. PSR has great potential to be applied as an alternative fuel for combustion process of industrial boilers in Malaysia. So many social and financial benefits such as more employment opportunities, reduction of dependency on imported fuel and healthier environment can be obtained by PSR utilization. Indeed, waste management strategies can be implemented best by clean energy generation. PSR can be developed with present manpower and material sources in Malaysia and electrical energy can be generated on a large scale at very low cost. PSR can be converted into useful energy by various methods such as direct combustion, gasification, pyrolysis and fermentation. Co-firing a fossil fuel like coal with PSR is the best system which has allowed PSR feedstock an immediate and cheap entry point into the energy market in Malaysia. Indeed, co-firing combustion of coal and PSR represents a cost-effective means for meeting more stringent emission targets and high electricity efficiencies. Malaysian palm oil mills can generate large amounts of electricity during palm harvesting and processing season. Furthermore, pollutant formation in co-firing biomass combustion can be mitigated drastically compared to the biomass direct combustion. Although PSR utilization in power generation can be presented in clean development strategies category, some financial barriers such as the lack of support from the Government for electricity generation and the lack of appropriate subsidies and tariff for PSR-fired electricity have discouraged Malaysian private sector investment in this field. However, the implementation of new policies and various plans for waste management have confirmed that the importance of solid waste utilization has been identified for the Government of Malaysia. Since Malaysia is one of the most important poles of biomass in the world, PSR as a great source of renewable energy should be taken into consideration in the energy mix of the country.

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